Andes system favor the flow along the meridians, especially in the United States. As a result, the number of cyclones crossing the United States is many times the number crossing Siberia, which is in fact singularly deficient in cyclones. South America shows a similar defect in circulation, because it lies too near the Tropical Zone.

The United States is covered by an active circulation between the Tropics and the north Polar regions, Siberia by a stagnant atmosphere, and Europe generally by a mixed and indifferent circulation, since the American cyclones tend to break up upon the territory of Europe after crossing the Atlantic Ocean. Hence, the region about the Indian Ocean is favorable for detecting direct synchronisms of pressure and temperature with the solar prominences by reason of its quiescent atmosphere, and the United States is well placed to respond to an inverse synchronism, by reason of its active circulation with a pronounced component from the north Polar regions. Europe does not possess an atmosphere which registers the solar and terrestial synchronism in a very efficient manner. This may account for the fact that the European attempts to establish a definite synchronism have issued generally with negative results. As has already been suggested, too much emphasis has been put upon the failures to make out the connection between the solar and the terrestrial synchronisms.

It should be noted that C. Nordmann[20] and A. Angot[21] deduced for certain tropical stations small residuals of temperature which are *inverse* to the sun-spot curve, but apparently synchronous. These authors have smoothed their curves by grouping successive years, and have reached small residuals. Since the synchronism should display the annual variations intact, as given above, it may be questioned whether any process for eliminating the minor deflections from year to year is desirable.

We also note the important fact that the wide amplitudes which are characteristic of the 11-year sun-spot curve, and which it has been chiefly sought to discover in the meteorological elements, does not, according to this research, appear at all prominently in the residuals. It is only the short period of about three years that displays the solar terrestrial synchronism. I am not, at present, able to indicate what this result implies in solar physics, but it certainly carries with it a change in our method of approaching the entire problem.

THE PROBLEM OF THE CYCLONE.

By F. J. B. CORDEIRO, dated Newport, R. I., September 5, 1902.[1]

It was Lord Kelvin who showed that a mass of fluid in vortex motion acquires all the properties of a solid, the chief of which are rigidity and elasticity. It was on this demonstration that he founded his astonishing vortex theory of matter. He showed perfectly that an atom of matter might possibly be nothing else than the frictionless fluid ether in a vortex state. A vortex in the ether would thus possess rigidity, elasticity, inertia, and all other properties of matter. In the same way a vortex in the atmosphere acquires shape and preserves it like any solid, as well as rigidity and elasticity. Professor Tait's smoke rings, which suggested to Lord Kelvin his ethereal vortex atoms, have all the properties of solid bodies. So, when I treat a revolving mass of air as being dynamically the same as a solid I do what Lord Kelvin has shown is perfectly admissible.[2]

Poisson's general equations for rotary motion of a solid having one fixed point O are given in most works on mechanics and read as follows:

$$(1)\qquad \begin{aligned} C\frac{dw}{dt} + u\cdot v\cdot(B-A) &= L,\\ B\frac{dv}{dt} + u\cdot w\cdot(A-C) &= M,\\ A\frac{du}{dt} + v\cdot w\cdot(C-B) &= N. \end{aligned}$$

In these equations u, v, and w are the angular velocities of rotation of a solid body with reference to the three coordinate axes, X, Y, and Z, fixed in space and intersecting at the fixed point O. A, B, and C are the moments of inertia of the solid mass with reference to its own three principal axes, the latter being in motion relative to the three fixed axes. L, M, and N are the moments of the accelerating forces that act upon the body from without taken with reference to the three principal axes.

If we apply these equations to a symmetrical solid of revolution, such as a ring, or an ellipsoid of revolution having its fixed point in its axis of figure, then we obtain the equations for the movement of a gyroscope or rotascope, or a top, and we are able to explain all the motions of those bodies with reference to the support on which they stand. If, however, instead of supposing the revolving body to have a fixed point, we give the latter also a definite motion, as, for instance, when the gyroscope, with its support, is carried with the earth around the earth's axis in its diurnal rotation, we can then deduce the movement of the gyroscope with reference to the meridian of the locality.

If the disk of the gyroscope be supposed to be horizontal, or nearly so, and revolving rapidly about an axis that is vertical, or nearly so, and if its axis is not constrained, but free to move on the earth's surface, we have a case apparently analogous to the movement of a cyclone or hurricane, at least in so far as the latter consists of a mass of air rotating in a horizontal plane. Practically the air within a cyclone is known to be either ascending or descending and changing continually, so that energy is brought into it from without and carried outward from it. If the energies thus added and lost counterbalance each other, we may perhaps hope to deduce from the laws of the gyroscopic motion of a solid some insight into the laws of the motion of the hurricane along the earth's surface.

The above general equations of rotation were in 1858 put into a convenient form for the study of the gyroscope by Major, afterwards General, J. G. Barnard, of the Army Engineers, and his paper is reprinted as No. 90 of Van Nostrand's Science Series.[3] In Major Barnard's little volume the reader will find deduced from fundamental principles the law of gyroscopic motion, which is this: If a spinning gyroscope or a spinning wheel be turned about an axis perpendicular to its own axis of rotation, a deflective force will be developed per-

[20] The periodicity of sun spots and the variations of the mean annual temperatures of the atmosphere. M. Charles Nordmann. Comptes Rendus. Paris, June, 1903. Translation in Monthly Weather Review, August, 1903. P. 371.

[21] The simultaneous variations of sun spots and of terrestrial atmospheric temperatures. Prof. Alfred Angot. Annuaire de la Société Météorologique de France, June, 1903. Translation in Monthly Weather Review, August, 1903. P. 371.

[1] The Editor has retained this paper for a year in hopes that the author would elaborate the mathematical deduction of the formulæ that he uses, but the latter has thought best to simply add a few references to the article by Major Barnard. The reader will find the phenomenon of the gyroscope treated in many modern works on mechanics. The fact that Mr. Cordeiro rests his theory entirely on the assumption that we may deal with the cyclone as if it were a rotating solid deprives his paper of any special interest to the student of hydrodynamics, but his results will, it is hoped, lead others to a more rigorous treatment of the subject.—ED.

[2] The vortex ring of Helmholz and Kelvin constitutes a different sort of motion from that within a cyclone and still more different from that of a simple gyrating mass moving like the particles of a spinning gyroscope. It is, therefore, quite hazardous to assume that the latter will show the mechanical peculiarities of the cyclone. The vortex theory of atoms has been abandoned.—ED.

[3] Analysis of Rotary Motion as Applied to the Gyroscope. By Major J. G. Barnard. D. Van Nostrand, publisher, New York, 1887.

pendicular to the plane in which it is turned. Furthermore, if the "spin" and the turn are both counter-clockwise, this deflecting force will be upward. The measure of this force is (see Barnard, pp. 44 and 57) clearly shown to be

$$g' = k^2 \cdot \frac{\omega}{R} \cdot \frac{d\psi}{dt},$$

where k is the "radius of gyration" of the gyroscope; ω is its angular velocity, or spin; R is the radius of the "turn," e. g., the radius of the earth, and $\frac{d\psi}{dt}$ is the angular velocity of the turning of the axis of spin, due to any cause, e. g., the diurnal rotation of the earth. (See fig. 1.)

This agrees perfectly with what we find in the motions of terrestrial cyclones. The rotation of a mass of air about its axis we may term its "spin;" the motion of the whole about the axis of the earth is its "turn." Therefore, the tendency to motion of the cyclone, as a whole, should, in the Northern Hemisphere, be toward the North Pole; in the Southern Hemisphere, where the spin and the turn are both clockwise as regarded from the outside, the tendency to motion should be toward the South Pole. Both these conclusions agree with the observed motions of the cyclones.[4]

[4] Meteorologists will not forget that in paragraph No. 31 of his classic treatise of 1857, "Motions of Fluids and Solids on the Earth's Surface," published in Runkle's Mathematical Monthly for 1858 to 1860, Prof. William Ferrel was the first to show that on the assumption that the motions of fluids are not resisted by the earth's surface or by their own internal viscosity, it follows that "if the fluid gyrates from right to left the whole mass has a tendency to move toward the north, but if from left to right, toward the south. If every part of a cylindrical mass having its axis of revolution vertical has the same angular velocity of gyration as in the case of solids, then, calling this velocity u, the preceding equation (51) gives for the accelerating force in the direction of the meridian

$$\frac{V}{M} = -\frac{g}{578}\,\frac{u \sin\psi}{n}\left(\frac{s'}{R}\right)^2 \qquad (52)$$

where g = terrestrial gravity. n = angular velocity of the earth's rotation. s' = small lineal distance from center to exterior of the gyrating mass. R = radius of the earth. ψ = colatitude or polar distance of the center of the gyrating mass of air. u = angular velocity of gyration of the mass."

Again, in articles 70 and 71 Ferrel says:

"The routes of cyclones in all parts of the world, which have been traced throughout their whole extent, have been found to be somewhat of the form of a parabola. Commencing generally near the equator, the cyclone at first moves in a direction only a little north or south of west, according to the hemisphere, when its route is gradually recurvated toward the east, having its vertex in the latitude of the tropical calm belt. This motion of a cyclone may be accounted for by means of what has been demonstrated in section 31, which is, that if any body, whether fluid or solid, gyrates from right to left, it has a tendency to move toward the north, but if from left to right, toward the south. Hence, the interior and most violent portion of a cyclone always gyrating from right to left in the Northern Hemisphere, and the contrary in the southern, must always gradually move toward the pole of the hemisphere in which it is. While between the equator and the tropical calm belt, it is carried westward by the general westward motion of the atmosphere there, but after passing the tropical calm belt, the general motion of the atmosphere carries it eastward, and hence the parabolic form of its route is the resultant of the general motions of the atmosphere and of its gradual motion toward the pole.

"It may be seen from equation (52) that the tendency of a gyrating mass to move toward the pole is as sin ψ or as the cosine of the latitude and also as the square of the diameter of the gyrating mass. Hence, near the equator, where the dimensions of the cyclone are always small, it moves slowly toward the pole, but as it gradually increases its dimensions, after passing its vertex, its motion toward the pole, and also its eastward motion, are both increased, and hence its progressive motion in its route or orbit is then accelerated, in accordance with the observations of Redfield.

"By comparing equations 27 and 44 it is seen that they are very similar, and consequently the motions which satisfy them must also be similar. Hence, the general motions of the atmosphere are similar to those of a cyclone. For the general motions of the atmosphere in each hemisphere form a grand cyclone having the pole for its center, and the equatorial calm belt for its limit. But the denser portion of the atmosphere in this case being in the middle instead of the more rare, instead of ascending it descends at the pole or center of the cyclone.

These violent revolving storms are usually generated on or near the equatorial border of the trade wind zones. The trade zones are usually separated by a belt called the doldrums, and all together follow the sun in its passage north and south. The southeast trades when they cross the equator assume a southwest direction, the cause of which is well understood; likewise the northeast trades become the northwest trades to the south of the equator. These opposing trades, though usually separated by a narrow belt of doldrums, at times become contiguous along an extended line. Now it can be demonstrated experimentally that when two opposing sheets of wind meet along an oblique line, a whirl will result in a direction from the obtuse toward the oblique angle.

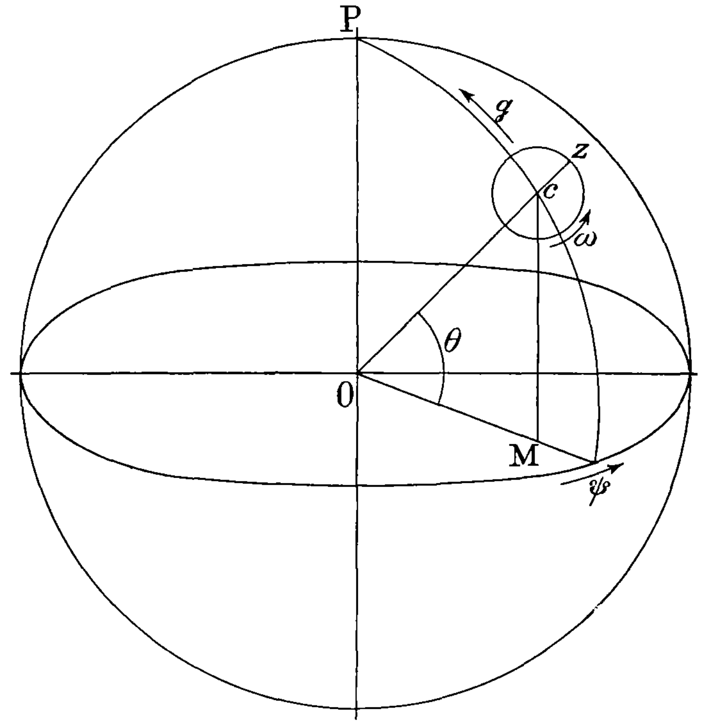

FIG. 1.—P = North Pole of the earth. O = center of the earth. Z = north pole of horizontal cyclone or gyroscope. C = center of cyclone or gyroscope. θ = latitude of C. $OC = R$ = radius of the earth. OM = radius of the small circle of latitude of the cyclone. ω = the spin of the gyroscope or cyclone about its vertical axis CZ in the direction of the arrow. ψ = the turn of the gyroscope or cyclone about OP in the direction of the arrow, due to the diurnal rotation of the earth. q = the deflecting force pushing the cyclone or gyroscope northward, due to the combined action of the spin of the cyclone and the rotation of the earth. The reader will please note that g in Fig. 1 should be q.

In the Northern Hemisphere the opposing trades meeting along a line obliquely will give rise to a contra-clockwise whirl, while in the Southern Hemisphere the whirl must be clockwise.

The ordinary explanation also that the sudden formation of a "low," by precipitation or otherwise,[5] must cause an inrushing of winds will, theoretically, in view of the earth's rotation on its axis, lead to the same results as above. In the one case the theoretical, in the other the experimental demonstration is perfect.

"The southern cyclone having the more rapid motions on account of the resistances from the earth's surface being less, causes a greater depression of the atmosphere there than does the northern cyclone in the Northern Hemisphere, and throws the calm belt a little north of the equator, as has been explained.

"The tendency of the smaller local cyclones, as has been seen, is to run into the centers of the grand hemispherical cyclones, and thus to be swallowed up and become a part of them."

[5] The precipitation of atmospheric moisture into rain or cloud does not directly form a low pressure. The attending evolution of latent heat causes the air and its moisture to simply delay their cooling, so that cloudy air, when freshly formed, is warmer than dry air would be. Of course in a short time the watery particles lose their heat by radiation,

But the object of this paper is to trace, if possible, the subsequent history of this rotating mass of air once it has been formed and become an entity separate from the rest of the atmosphere. Thanks to the labors of Redfield, Reid, Ferrel, and others, we have learned that this rotational energy once started is not easily dissipated, but persists for days and sometimes for weeks. There are undoubtedly many slight whirls, lacking energy and extent, which are soon extinguished by counteracting forces. We shall deal, therefore, only with such vortices as have sufficient energy to preserve a constant rotational energy. Every cyclone must sooner or later be dissipated, but many preserve their energy by precipitation or otherwise, long enough to serve for purposes of investigation. The problem is so complex and so many factors enter into it that an exact solution is impossible. To quote Lord Kelvin: "We may, therefore, at once say that there is no question in physical science which can be *completely* and *accurately* investigated by mathematical reasoning, but that there are different degrees of approximation, involving assumptions more and more nearly coincident with observation, which may be arrived at in the solution of any particular question." We shall attempt, therefore, only approximations, and, while considering the various forces at play, neglect those that we can in the cause of simplicity.

In the first place we shall assume that the rotational energy of the cyclone remains constant during the time it is studied. Now, this will not always be the case. We shall see later on that this quantity may change almost abruptly, but within certain selected limits such an assumption is not inconsistent with tangible results, and, therefore, this is an approximation which, in most cases, will not lead to very large errors. Let ω be the angular velocity of the cyclone and h its radius of gyration, while M is its mass. We postulate, therefore, that the rotational energy or $\frac{M h^2 \omega^2}{2}$ remains constant within the limits of study. If this were not so, the problem could not be attacked, since there could be no ascertainable law by which this energy varied. Now, every one who has studied the subject of hurricanes must have been struck by the remarkably regular curves these bodies trace upon the surface of the earth. The cyclone moves as a whole and in a very regular way. The explanations of this motion have been of the vaguest and, so far as the writer knows, there have been only four:

(*a*) One is that they are blown along by the prevailing winds; but an attempt to verify this would lead only to contradictions, for two cyclones often follow each other over the same area within a short time and pursue utterly different paths. It is hardly necessary to pursue this further.

(*b*) Again, they have been thought to be guided by the coast line, but we shall see later on that this is probably ascribing a cause to an effect. Besides they manage to get along very well without any coast lines.

(*c*) Another explanation has been given that they are influenced by or follow up the Gulf Stream. This is in reality no explanation at all. Besides they do not do so, and they pursue their regular courses where there is no Gulf Stream or any regular current for that matter.

(*d*) Lastly it is customary in official weather reports to read of a cyclone having been "deflected by an area of high pressure" at some distant region. But an examination will show that they move away from or toward areas of high pressure as it may happen, modifying these areas where they reach them, but never being influenced by them.[6]

Now, a cyclone, since it revolves simultaneously about its own axis and about the axis of the earth, is what is known dynamically as a gyroscope. In mechanics we have many instances in which gyrostats, by their motion, reveal the motion of the earth about its axis, and this motion can be calculated by a knowledge of the restraints imposed and the forces applied. In the same manner the motion of a cyclone reveals the motion of the earth about its axis.

It is the object of this paper, if nothing more, to demonstrate that the motion of a cyclone is due to its own intrinsic gyroscopic forces, in other words, that it is a simple question of the dynamics of a certain mass of air revolving about its own axis and the axis of the earth, and of the forces impressed upon it. Further than this, an attempt will be made to calculate this motion and compare it with the observed motion.

A cyclone at the moment of its formation may be stationary relatively to the earth or it may be launched with a velocity relative to the earth's surface in any direction, but in either case, the forces brought into play will soon steady it and start it out upon its proper course.

Chief of these forces is the friction of the earth's surface. We shall consider a cyclone as a material revolving disk, separate and distinct from the remaining atmosphere. This disk has an area immensely greater than its thickness. Consequently, the immense momentum of this mass, moving with its thin edge through the atmosphere, will cause it to meet with no appreciable resistance from this source. It is not certain that we are justified in neglecting this resistance, but the fact that results, calculated on this assumption, agree tolerably well with what is actually observed lead us to believe that we do no great wrong.

But the friction of the cyclone over the earth's surface, both rotational and transitional, must be very great. We see this in the appalling destructive effects of a hurricane, and in the tremendous seas that are raised. Unfortunately the theory of the friction of gases on solids and liquids has never been thoroughly worked out.[7] For lack of further knowledge, we shall assume that this resistance is proportional to the opposed surface and is proportional to the first power of the velocity. It probably also depends somewhat upon the pressure, but this does not concern us, since the pressures throughout remain tolerably constant. We make this assumption because it agrees approximately with the observed facts. It is well to bear in mind that this is probably only an approximation and may be found later on not to be true.

Now, this frictional couple will tend to oppose the rotational energy of the cyclone and bring it to rest, but we have assumed that the cyclone is continually acquiring enough energy from precipitation to preserve its rotational energy tolerably constant.

The component of this frictional couple, however, perpendicular to the earth's axis, will tend to twist it backward about

and the cloud becomes cold. The fall of rain from the cloud is not sufficient to relieve the atmosphere of any great amount of weight, and does not explain the formation of "areas of low pressure." Again, the ascent of a stream of hot air does not directly form a low pressure. The difference in pressure between the top and bottom of a mass of warm air constitutes the so-called buoyancy, and the air will start into an ascending motion when this difference is exceedingly small. The low pressures shown upon our weather maps are not the cause of the inrushing of winds, but on the contrary it is the inappreciable barometric disturbances, so delicate that they are not shown upon our weather maps that cause the inrushing winds: then, the winds, combined with the rotation of the earth on its axis, cause the deeper low pressures that are shown on the daily weather map.

[6] The reader should consult the memoir by the editor, Preparatory Studies for Deductive Methods in Storm and Weather Predictions. Annual Report, Chief Signal Officer, 1889, Part II.—ED.

[7] As the surfaces of the earth and ocean are very rough, they offer a resistance to the motion of the atmosphere, which is a very complex matter, and is mainly made up of what I have called convectional resistances. These resistances are the principle subject of study in the so-called tumultuous motion of liquids and gases, which have been elaborately treated by Boussinesq. For perfectly smooth, solid surfaces, we have to deal only with the viscosity of the fluid. For smooth liquid surfaces, the flow of a gas parallel with the surface gives rise to instability and complex wave motions discussed by Kelvin and especially by Helm holz. Translations or abstracts of these papers are easily accessible.—ED

this axis. In other words, the moment of the momentum of the cyclone as a whole about the earth's axis will continually be diminished.

Now, the projection of the surface of our cyclone upon an equatorial plane increases as the sine of the latitude. It is evident, therefore, that this frictional couple about an axis parallel to the earth's axis will increase as the cyclone moves north (or south for the Southern Hemisphere). In other words, the moment of momentum of the cyclone about the earth's axis will decrease more rapidly the farther north it moves. Now, we have assumed that the frictional resistance is proportional to the surface; the forces of the friction couple, therefore, vary proportionately to the sine of the latitude, but the arm of the couple also increases as the sine of the latitude. It follows then that the moment of the couple tending to reduce the moment of momentum of the cyclone about the earth's axis will increase as the square of the sine of the latitude. The moment of momentum of a cyclone about the earth's axis will, therefore, decrease very much more rapidly in a high than in a low latitude. Mathematically expressed we can put our law in the following form:

$$MR^2 \cos^2 \theta \frac{d\psi}{dt} + Mk^2\omega \sin \theta = C - \int k \sin^2 \theta \, dt,$$

where R=radius of the earth=3437 nautical miles, or 3958 statute miles.

$\frac{d\psi}{dt}$=angular velocity of the cyclone about the axis of the earth and θ is the latitude. M is the mass of the cyclone.

The second term $Mk^2\omega \sin \theta$ represents the component of the moment of momentum of the cyclone due to its proper rotation about an axis parallel to that of the earth. Since it is probable that the moment of momentum of the cyclone about its own axis is small relatively to the momentum of the whole mass about the axis of the earth we shall neglect this term. In doing so we shall introduce a certain amount of error and for more accurate work it would probably be advisable to take cognizance of it. It is difficult to conceive of a greater moment of momentum of a cyclone about its axis than 10,000 M, while the moment about the axis of the earth is very much larger. However, we are here merely sketching a method of attacking the problem.

We shall write, therefore, as an approximate formula

$R^2 \cos^2 \theta \frac{d\psi}{dt} = c - \int k \sin^2 \theta \, dt.$ Let us apply this formula to the Porto Rican hurricane of August, 1899.

At 8 p. m. of August 7 its center was in latitude 16° 50′, and it was traveling with a westward velocity of 13 miles per hour. At 8 p. m. of August 8 its center was in latitude 18° 50′, and it had a westward velocity of nearly 8 miles an hour.

Since at the first point the earth moves 861.5 miles per hour, and at the second point 851.8 miles per hour, the actual velocity of the cyclone at the two points was 848.5 and 844 miles per hour, respectively. The moment of momentum in the first position was, therefore, 2,791,300; in the second position 2,745,700. The difference = 45,600 = $k \sin^2$ 17° 50′ since we take the average value of the latitude for the twenty-four hours. $\therefore \log k = 5.686815$.

Now, let us compute the retarding effect of the friction for some subsequent period of twenty-four hours. We find that at 8 a. m. of August 13 the center of the cyclone was in latitude 27°; at 8 a. m. of August 14 the center was in latitude 29° 30′.

In the former position it was moving about one mile to the westward per hour; in the latter position it was moving directly northward. The moments of momentum were respectively 2,453,000 and 2,343,200. The decrease, therefore, was 109,800. But by our formula we can compute this decrease. Since the average latitude for the period is 28° 15′; we have

$$\log \sin^2 28° \, 15' = 9.350310$$
$$\log k = 5.686815$$
$$\overline{\quad 5.037125 \quad}$$

the product corresponds to 108,925.

The agreement in this case is very close. However, to plot the position of the center of a cyclone accurately is very difficult as well as the determination of its speed at a given point, so that we may expect a moderate difference between the observed and computed values. Their general agreement, however, in a number of cyclones which the writer has studied, leads him to believe that the law is a close approximation, perhaps actually true.

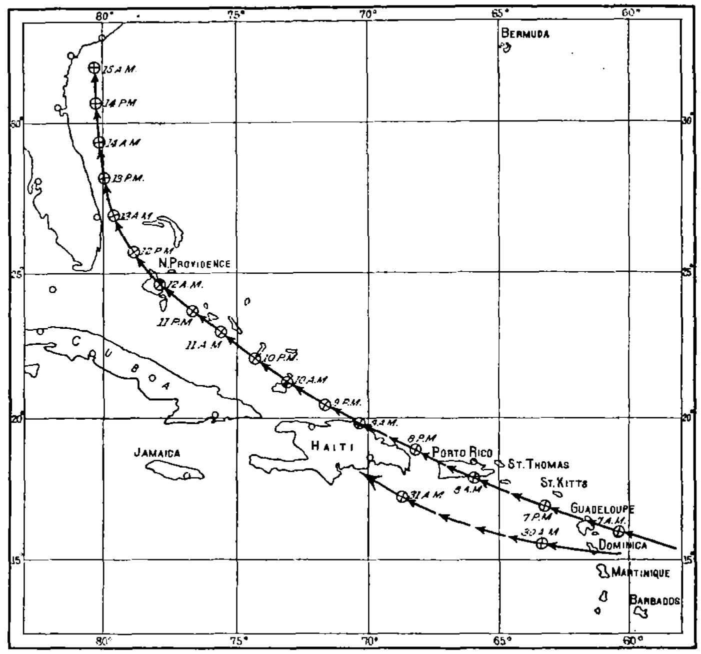

FIG. 2.—Porto Rican hurricane of August 7, 1899.

Let us consider the intermediate portion of the same cyclone. At 8 a. m., August 10, the center was in latitude 21° 20′ and was traveling westward 6 miles an hour. At 8 a. m., August 11, the center was in latitude 23° and was still going westward at about the rate of 6 miles an hour.

Moment of momentum at first point	=	2, 665, 250
Moment of momentum at second point	=	2, 602, 240
Difference	=	63, 010

Now, the average latitude for the period was 22° 10′.

$$\log \sin^2 22° \, 10' = 9.153378$$
$$\log k = 5.606815$$
$$\log 69,210 = 4.840193$$

It may seem that this is not a very close agreement, but it is within the limits of accuracy with which the positions can be plotted.

These positions have been taken from the Weather Bureau chart and are interpolations, but surprisingly accurate, considering that in this portion of its track the storm was at sea, far removed from all observation stations. If, for instance, the position at 8 a. m., August 10, was latitude 21° 10′ instead of 21° 20′, as we took it above, the observed and computed values in question would be 68,560 and 68,720, respectively.

The Porto Rican hurricane, therefore, throughout its course, as given by the Weather Bureau, followed very closely the law

$$R^2 \cos^2 \theta \frac{d\varphi}{dt} = C - K \int \sin^2 \theta \, dt,$$

and the same has been found to be the case with some other hurricanes, for which the writer has been able to obtain reliable data. In some other cases the agreement is not so close.

We shall now consider the strictly gyroscopic character of the cyclone. Since it is whirling about its own axis and at the same time about the axis of the earth, a polar acceleration must be developed. This can be easily demonstrated by a toy gyroscope. If such a gyroscope as is shown in fig. 3 be held in the hand and given a smart spin counter clockwise and then turned in the direction indicated by the arrow, imitating the motion of a cyclone, a strong force will be felt, tending to raise the instrument. The law of the gyroscope is that if the axis be turned about some fixed point, a force will be developed normal to the plane in which the axis is turned. When the two rotations are as in the figure, this normal deflecting force will be upward.

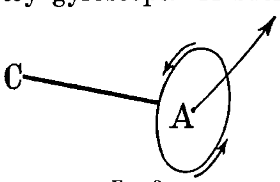

FIG. 3.

Further, this force will be equal to $g = \frac{k^2\omega}{R}\frac{d\psi}{dt}$, where k and ω are, respectively, the radius of gyration and the angular velocity of the gyroscope, and $\frac{d\psi}{dt}$ is the angular velocity with which the axis is turning. R is the radius with which the axis turns, or the distance CA. This explains the constant northing or southing in the respective hemispheres which is observed in all true cyclones.

Now, if our cyclone moved over the surface of the earth without any friction it would be easy to compute its motion. If θ represents its latitude at any point, and ψ its longitude, and we suppose it to start from some point (θ_o, ψ_o), the differential equations of the motion would be

1 $$\frac{k^2\omega}{R}\frac{d\theta}{dt} = -D_t\left(R\cos\theta\frac{d\psi}{dt}\right) \text{ and}$$

2 $$\frac{k^2\omega}{R}\cos\theta\frac{d\psi}{dt} = R\frac{d^2\theta}{dt^2},$$

where R, of course, represents the radius of the earth. If we represent the actual horizontal velocity of the cyclone by v_h and the polar velocity by v_p and integrate[7] the above equations, we have

$$v_h = V - \frac{k^2\omega}{R}(\theta - \theta_o)$$

and

$$v_p^2 = 2\frac{V}{R}k^2\omega(\theta-\theta_o) - \left(\frac{k^2\omega}{R}\right)^2(\theta-\theta_o)^2.$$

V represents the initial velocity of the starting point or the velocity with which this point on the earth's surface is moving about the earth's axis. In such an ideal frictionless case it is easily seen that the resultant velocity is $v_h^2 + v_p^2 = V^2$. And this must be the case, since no energy is expended. But the forces which we are considering, in moving the cyclone over the earth's surface, have to do considerable work in overcoming friction. Consequently the sum total of the energy of the system is continually diminishing, albeit the rotational energy of the cyclone may be preserved nearly constant by energy acquired from precipitation.

As the frictional couple which we have considered in connection with the moment of momentum must affect chiefly the horizontal velocity, it will be at once seen that the equation $v_h = V - \frac{k^2\omega}{R}(\theta - \theta_o)$ can not hold for a cyclone. The polar velocity, however, will not be so much influenced, and it is probable that the law

$$v_p^2 = 2\frac{V}{R}k^2\omega\ (\theta-\theta_o) - \left(\frac{k^2\omega}{R}\right)^2(\theta-\theta_o)^2$$

may approximately hold. Stated in general terms this law can be written

$$v_p^2 = K(\theta-\theta_o) - K^1(\theta-\theta_o)^2$$

where the constants will depend upon our selection of units. Let us apply this to some actual cyclones. I have taken two of these as charted by Piddington (Sailor's Hornbook) from data given by Reid and Redfield. The first originated in latitude 15° north, longitude 77° west, September 27, 1837.

We must bear in mind the difficulty even to-day of plotting accurately the position of a cyclone center, and that, therefore, the daily positions as given by Reid and Redfield may be subject to some error. We shall, therefore, aim only at approximate results. Let us take our velocities in nautical miles per hour, and our latitude in degrees reckoned from the starting point, viz, 15°.

We find that from September 27 to 28 it was moving northward about 3 miles an hour. Again from October 9 to 10 it had about that same velocity. Substituting in our equation $v_p^2 = K\theta - K^1\theta^2$ we have $9 = K - K^1$ and $9 = 19K - 361K^1$. $\therefore K = 9.47$ and $K^1 = 0.47$. From the formula we see that v_p has a single maximum velocity, and this occurs where $K = 2K^1\theta$. In the present case this would correspond to about latitude 25°; and the velocity itself is $v_p^2 = 94.7 - 47 = 47.7$. The maximum velocity is therefore, about 7 miles per hour, which corresponds with that which actually occurred.

Piddington charts a cyclone which began some time in October, 1846, in latitude 14° north and longitude 77.5 west. He plots only the positions it had on October 11, 12, 13, and 14. On October 11 the center is plotted at latitude north 25°, and going northward at the rate of 15 miles an hour. On October 12 it was at 31° north latitude, and traveling northward at the rate of 17.5 miles an hour. We can, therefore, write

$$225 = 11K - 121K^1$$
$$306 = 17K - 289K^1$$

whence

$$K = 26.63$$
$$K^1 = 0.33.$$

October 13 the cyclone is plotted at latitude 38° north. Let us see what the poleward velocity should be: $v_p^2 = 24K - 576K^1$, therefore, $v_p = 21$. Actually it was about 22.5. We also find that this cyclone would have attained its maximum poleward velocity in latitude 54°, and not, as in the previous cyclone, at about the point of recurvation. From these two examples, as well as from a number of others, we may conclude that the poleward velocity is approximately that due to the gyroscopic forces generated, and is not influenced much by frictional forces. But that it is to some extent influenced by such forces must be self-evident.

The object of the writer will have been satisfied if he has demonstrated why a cyclone moves, and how the nature of this motion is dependent upon the forces called into play. The

[7] The successive steps of the integration of these equations are as follows. Integrating (1) we have

$$k^2\frac{\omega}{R}\cdot\theta = -R\cos\theta\frac{d\psi}{dt} + K$$

where K is a constant, depending upon the initial conditions of motion. If the cyclone starts from latitude θ_o with the same velocity as the surface of the earth at that point, we have

$$v_h = V - k^2\frac{\omega}{R}(\theta - \theta_o)$$

where v_h represents the velocity at any time projected upon the plane of the equator.

Since, after the initial impulse, no forces are supposed to act on the gyroscope, the velocity, V, must remain constant throughout. Therefore, $v_h^2 + v_p^2 = V^2$, hence,

$$v_p^2 = 2Vk^2\frac{\omega}{R}(\theta-\theta_o) - \left(k^2\frac{\omega}{R}\right)^2(\theta-\theta_o)^2.$$

These equations represent the motion of a frictionless cyclone, as has been stated before, but applying the correction for friction, we get the motion of a natural cyclone.

question naturally arises whether it is possible, or will ever be possible, from a few given initial positions to predict the subsequent path. It will be noted that in the whole preceding discussion the energy of rotation of the cyclone has been supposed to be constant, or at least constant within certain limits. Now, this is never actually the case, though very often it is approximately so.

In the case of the last cyclone discussed it would be possible to trace its course beyond October 13, although no further record has been left us. By the law of the diminishing moment of momentum we might obtain the relative horizontal velocity for the 14th, and this, with the polar velocity which we have already calculated, would give us its position for that day. We could then plot its course for the next day, and the next, and although this path would not coincide with the one actually traced, it would give us an approximate idea of its subsequent course. But although many cyclones might have their paths predicted in advance with more or less accuracy, it is certain that others could not. The course of the Galveston hurricane could not in any way have been foreseen up to the morning of the 6th of September, 1900. Previous to that time it was a general disturbance of no very great intensity, extending over pretty much the whole of the Caribbean Sea. It is extremely difficult to plot the center of this disturbance from day to day, and, therefore, it is out of the question to attempt to deal with it analytically. But after the 6th it contracted, concentrating its energy, and becoming for all practical purposes a totally new and different cyclone. Such an abrupt change in the parameters can not be dealt with.

The problem of forecasting the track of a cyclone may later on, with increasing knowledge and more accurate measurements, be placed upon an entirely satisfactory basis. The present paper is merely a preliminary sketch, discussing the nature of the problem and giving some hints as to how it may be attacked.

In this article I have not "picked out a few cases of close agreement," but simply used the very meagre material accessible to me. It is my earnest desire to get more data of a reliable nature, and eventually find an opportunity to analyze the motion of hurricanes.

I believe that I have shown that the motion of cyclones is due to ordinary dynamical laws inherent in themselves. In some cases this motion can be predetermined. I do not pretend to say at present that the path of every cyclone can be predicted, especially where the governing quantities, or the *parameters* are changing in no ascertainable way—but in a number of cases where the moment of inertia remains tolerably constant, or where there is a constant rotational energy, as is the case in the heavy tropical hurricanes, we may predetermine a path with a considerable degree of accuracy.

Before closing, the writer desires to call attention to the remarkable conformity existing between our cyclone curves and the disposition of the coast line throughout the West Indies and the North American Continent. The Greater Antilles, the Gulf of Mexico, and the Atlantic coast line are arranged along cyclone curves. This has led some writers to ascribe the form of the cyclone path to the configuration of the coast line. The exact opposite is probably the fact.

RECENT PAPERS BEARING ON METEOROLOGY.

Dr. W. F. R. PHILLIPS, Librarian, etc.

The subjoined titles have been selected from the contents of the periodicals and serials recently received in the Library of the Weather Bureau. The titles selected are of papers or other communications bearing on meteorology or cognate branches of science. This is not a complete index of the meteorological contents of all the journals from which it has been compiled; it shows only the articles that appear to the compiler likely to be of particular interest in connection with the work of the Weather Bureau. Unsigned articles are indicated by a ——.

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- **Higginson, E.** Climate of Peru. P. 282.
- **Marriott, W.** The Frost of April, 1903. Pp. 283-288.
- —— Cricket and Rainfall. P. 288.
- —— Lightning Photography. P. 288.
- **Baxendell, J.** Description of the Dines-Baxendell Anemograph, and the Dial-Pattern Non-Oscillating Pressure-Plate Anemometer. Pp. 289-298.
- —— The Employment of Means in Meteorology. P. 298.
- **Dines, W. H.** Investigation of the Upper Atmosphere by Means of Kites. Pp. 310-311.
- **Starr, W. H.** Climate of Wei-Hai-Wei. Pp. 312-313.
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